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Principal component and PLS discriminant analyses applied on skulls of European shrews of the genus *Sorex* (Mammalia, Soricidae)

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Abstract. Skulls of nine species of shrews of the genus *Sorex* were measured on an image analyzer. 120 measurements were taken on each skull. The measurements were then statistically analysed by using the multivariate projection methods principal component analysis (PCA) and PLS discriminant analysis combined with crossvalidation. The analyses showed good separation between all species. It was discussed whether this class separation reflected the phylogeny or different ecological adaptations.

Key words. Shrews, skulls, phylogeny, principal component analysis, PLS discriminant analysis.

Introduction

At least thirteen species of the genus *Sorex* occur in the western Palaearctic except for North Africa and most of the Middle East. The species concerned are *S. alpinus*, *S. araneus*, *S. caecutiens*, *S. caucasicus**), *S. coronatus*, *S. granarius*, *S. isodon*, *S. minutissimus*, *S. minutus*, *S. raddei*, *S. samniticus*, *S. "tundrensis"* (the status of the Eurasian animals earlier placed in *S. arcticus* is still not clear, Kozlovsky 1971 found *S. irkutensis* and *S. sibiriensis* to be distinct karyotypically) and *S. volnuchini*. Two additional species, *S. daphaenodon* and *S. vir* (probably identical with *S. roboratus* of the Altai, see Hoffmann 1985) occur in Siberia almost west to the Ural mountains, but are not yet known from Europe.

The distributions of the fifteen species named above are chiefly of two different types. Many species have large west-east distributions chiefly in the taiga zone of Eurasia though some (e. g. *S. araneus* and *S. minutus*) also occur south of the coniferous forest-zone. Of these species *S. araneus* and *S. minutus* might be regarded as mainly European. They occur over large areas in Europe but in Asia they only reach eastward to the Yenisei River and Lake Baikal, while *S. caecutiens*, *S. daphaenodon*, *S. isodon*, *S. minutissimus*, *S. "tundrensis"* and *S. vir* all might be regarded as mainly Asian; their European distribution is (if they occur at all) limited while in Siberia they all reach eastward to the Pacific Ocean (Dolgov 1967, Honacki, Kinman & Koeppl 1982).

Another type of distribution is shown by *Sorex*-species occurring in rather limited, chiefly mountainous areas in southern Europe. Such forms occur in Spain (*S. granarius*) and in the Caucasus (*S. caucasicus*, *S. raddei* and *S. volnuchini*). *S. alpinus*

*) Note added in proof = *S. causasicus* should, according to Zaitsev, Zool. Zh. 67: 1878—1888, 1988, be called *S. satunini*.

is spread over a large area in south and central Europe but again chiefly at higher altitudes while *S. samniticus* occurs in lowlands in Italy. All these distributions might be regarded as relic distributions.

The only species not showing either a continuous west-east distribution in the north or a relic distribution in the south is *S. coronatus* in southwestern Europe. This form probably linked off from *S. araneus*-like forms during the last glaciations.

The relationships of these species are not completely clear. *S. araneus*, *S. caucasicus*, *S. coronatus*, *S. daphaenodon*, *S. granarius* and *S. tundrensis* together with *S. arcticus* of North America and *S. asper* of the Tien-Shan (Ivanitskaya et al. 1986) form the *S. araneus/arcticus*-group characterized karyologically by two-armed x-chromosomes and (in males) two y-chromosomes (Hausser et al. 1985). This group probably represents a monophyletic unit.

Of the other species, *S. caecutiens*, *S. isodon*, *S. minutissimus*, *S. minutus*, *S. raddei*, *S. vir* and *S. volnuchini* all have karyotypes with either the chromosomal number of 42 or a chromosomal number close to or possibly derived from 42 (Fedyk & Ivanitskaya 1972, Ivanitskaya et al. 1986). This group might not be a monophyletic unit; according to Fedyk & Michalak (1982) the similarity of the number of chromosomes in *S. minutus* on one hand, and *S. isodon*, *S. vir* etc. is fortuitous.

Finally, *S. alpinus* and *S. samniticus* have karyotypes very different from the other species and also from each other (Meylan 1964, Graf et al. 1979). These two species appear not to be closely related to any other living *Sorex*-species; they might be relic forms of two otherwise extinct branches of the genus.

The aim of this paper was to statistically analyse the morphology (chiefly expressed by measurements) of shrew skulls and compare the patterns of relations between different species thus obtained, to those obtained using karyological methods.

Relationships between different species are not necessarily reflected in skull morphology. *S. alpinus*, the most isolated species karyologically, is certainly also the most isolated in gross morphology, while *S. samniticus* is morphologically very similar to *S. araneus*, *S. coronatus* and *S. granarius*, which are members of the *S. araneus/arcticus*-group. The morphological and genetic differentiation of the latter four species has been statistically treated by Hausser (1984). A limitation in univariate statistical methods is that each variable is treated separately. This might lead to unwarranted results. "Class differences are not clearly seen in the individual variables. The classes are separated by a *combination* of the variables" (citation from Wold et al. 1983).

Models like SPSS (used by Hausser) and SIMCA (used here) are, however not "one variable at a time" models. Thus in this work principal component analysis and partial least squares (PLS) discriminant analysis have been used. These methods are multivariate and deal with all variables simultaneously.

Material and methods

19 skulls each of *S. alpinus*, *S. araneus*, *S. caecutiens*, *S. coronatus*, *S. isodon* and *S. minutus*, 13 of *S. granarius* and *S. samniticus* and 7 of *S. minutissimus* were measured on an image analyser (MOP Videoplan, Kontron image analysis division, Zeiss), connected to a dissecting microscope (19 were measured because there were 19 channels in each file on the image analyser). The animals were obtained from the Swedish Museum of Natural History,

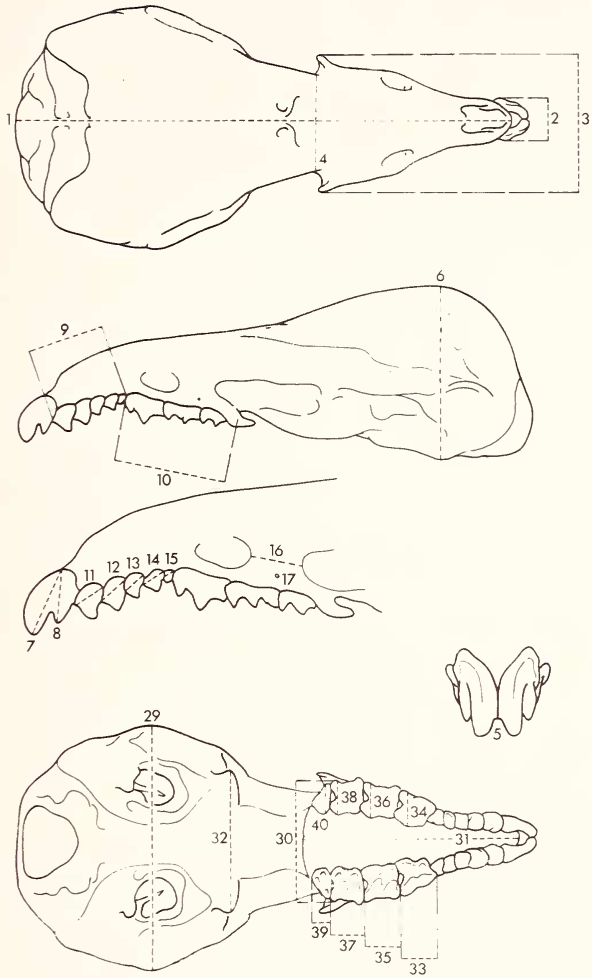

Fig.1: Cranial measurements taken for this study. Explanations of figures are given in the text.

Stockholm, from the University of Oulu, Finland and from the Université de Lausanne, Switzerland. The geographical origin of the animals is given in Table 1. Other species mentioned in the introduction were not available to me.

From each individual 120 measurements were taken (see Figs 1—2). Most of them were metrical measurements, but some characters such as the position of the mental and lacrimal foramina, size and pigmentation of cusps of upper molars, or the angle between the coronoid process and the articular facets of the mandibular condyle.

These characters were treated in the following way. Taking the position of the mental foramen as an example this character was given the value 1 if the foramen was placed under P_4, the value 2 if it was under P_4—M_1, the value 3 if it was situated under the foremost part of the trigonid of M_1, the value 4 if it was placed centrally under the trigonid of M_1 and so on, up to the value 8. Another example can be given like size and pigmentation on the hypocone of M^1. In this case the character was given the value 1 if the hypocone was absent, the value 2 if it was rudimentary, the value 3 if it was distinct but unpigmented and the value 4 if it was distinct and pigmented.

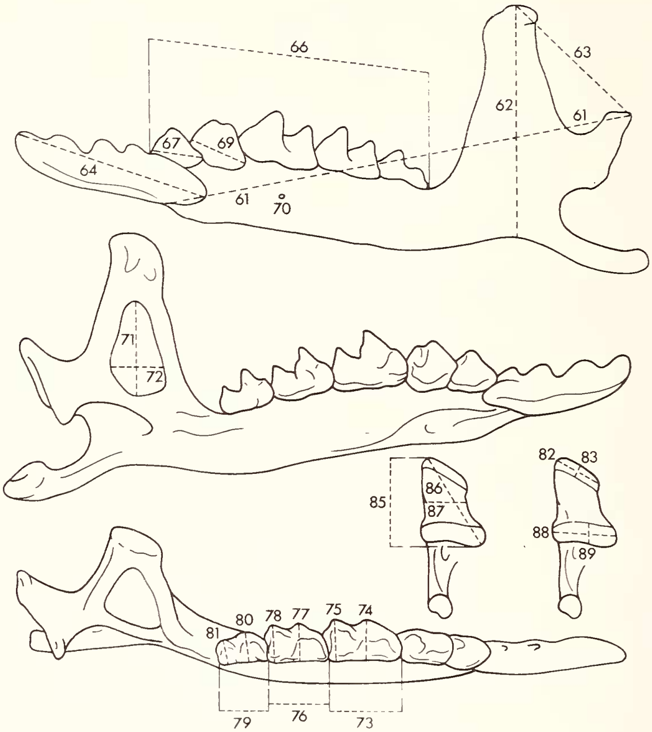

Fig. 2: Mandibular measurements taken for this study. Explanations of figures are given in the text.

Table 1: Number of skulls of each species.

Species	Number of skulls	Geographical area	Source
Sorex alpinus	19	Switzerland, Germany, Yugoslavia	1, 3
Sorex araneus	19	Sweden, Finland, Germany, Czechoslovakia	1
Sorex caecutiens	19	Sweden, Finland	1, 2
Sorex coronatus	19	Switzerland	3
Sorex granarius	13	Spain	3
Sorex isodon	19	Finland	2
Sorex minutissimus	7	Finland	2
Sorex minutus	19	Sweden, Germany	1
Sorex samniticus	13	Italy	3

Source: 1 = Swedish Museum of Natural History, Stockholm, Sweden
2 = University of Oulu, Finland
3 = Université de Lausanne, Switzerland

Most measurements were taken on both the left and the right side of the skull which accounts for the high number of measurements. The characters measured are given below, characters given as values are in parentheses.

A. On the skull.
1. Condylobasal length.
2. Breadth of rostrum taken over upper incisors.
3. Maxillary breadth.
4. Interorbital breadth.
(5. Occurrence and size of medial tines on upper incisors.)
6. Cranial height.
The following measurements (7—17) taken on the left side.
7. Length of the first cusp of the upper incisor.
8. Length of the second cusp of the upper incisor.
9. Total length of the upper antemolars.
10. Total length of the upper molariform teeth.
11.—15. Length of A^1—A^5 respectively.
16. Breadth of the zygomatic plate.
(17. Position of the lacrimal foramen.)
18.—28. = 7.—17. from the right side.
29. Cranial breadth.
30. Width of M^2—M^2.
31. Palatal length.
32. Glenoid width.
Measurements 33—46 taken of left side.
33. Buccal length of P^4.
34. Width of P^4.
35. Buccal length of M^1.
36. Posterior width of M^1.
37. Buccal length of M^2.
38. Posterior width of M^2.
39. Length of M^3.
40. Width of M^3.
(41. Size and pigmentation of the protocone on P^4.)
(42.—44. Size and pigmentation of the hypocones on P^4—M^2.)
(45. Size and pigmentation of the metacone on M^3.)
(46. Size and pigmentation of the protocone on M^3.)
47.—60. = 33.—46. from the right side.
B. On the lower jaw (61.—90. taken on the left lower jaw).
61. Length of the mandible.
62. Height of the coronoid process.
63. Distance between coronoid process and the upper articular facet of the mandibular condyle.
64. Length of the lower incisor.
(65. Number of cuspules on the lower incisor.)
66. Length of mandibular toothrow (except incisor).
67. Length of A_1.
(68. Number of cusps on A_1.)
69. Length of P_4.
(70. Position of mental foramen.)
71. Height of the internal temporal fossa.
72. Width of the internal temporal fossa.
73. Length of M_1.
74. Trigonid width of M_1.
75. Talonid width of M_1.
76. Length of M_2.
77. Trigonid width of M_2.

78. Talonid width of M_2.
79. Length of M_3.
80. Trigonid width of M_3.
81. Talonid width of M_3.

Measurements 82.—90. taken on the mandibular condyle.

82. Length of upper condylar facet.
83. Thickness of upper condylar facet.

(84. Angle between coronoid process and upper condylar facet.)

85. The height of the condyle.
86. Greatest condylar depth.
87. Width of interarticular area.
88. Length of lower condylar facet.
89. Thickness of lower condylar facet.

(90. Angle between coronoid process and lower condylar facet.)

Measurements 91.—120. = 61.—90. from the right side.

The two projection methods principal component analysis (PCA) (Joliffe 1986) and partial least squares (PLS) discriminant analysis combined with cross validation (Ståhle & Wold 1987, 1988) have been applied.

The PCA can very well be used for recognizing similarities between objects in one class and dissimilarities between objects in different classes and can also be applicated on both continuous and non-continuous variables at the same time (Joliffe 1986).

The PLS discriminant analysis is a new type of discriminant analysis different from linear discriminant analysis (LDA). The PLS approach, which operates on the original variables space, has the advantage that it can deal with highly correlated variables and be applied to problems where the number of variables is high and even exceed the number of observations. The results from PLS can preferably be presented in object and variable related projections with the same interpretation as object and variable related PCA projections.

The calculations have been performed with the SIMCA (Soft Independent Modelling of Class Analogy) pattern recognition package as described by Wold et al. (1983, 1984). Prior to the analysis all variables were scaled variable-wise to zero mean and unit variance. The results were presented in plots where the different species fell apart. Also the variables (measurements) were plotted against each other, in order to recognize the variables that were chiefly responsible for separating the different species.

Results

A. All species

In the first PCA (Fig. 3a—c), all nine species were included. The first projection (X = PC 1, Y = PC 2) clearly showed that *S. alpinus* was distinctly separated from all other species. It also showed a division of the remaining species into two groups, one containing *S. araneus*, *S. coronatus*, *S. granarius*, *S. isodon* and *S. samniticus* and the other consisting of *S. caecutiens*, *S. minutissimus* and *S. minutus*. In this latter group *S. minutissimus* was clearly separated from the other two species. 53.1 % of the variance was explained by this component. The second projection (X = PC 1, Y = PC 3) which explained 8.9 % of the total variance confirmed the separation of *S. caecutiens*, *S. minutissimus* and *S. minutus* from the other species (however, without setting *S. minutissimus* apart from the other two species) and finally the projection of the second and third component (X = PC 2, Y = PC 3) confirmed the separation of *S. alpinus* from all other species, and explained 6.05 % of the total variance. In both these two latter projections there were some outliers of *S. araneus*. Together the three projections explained 68.0 % of the variance. A variable loading

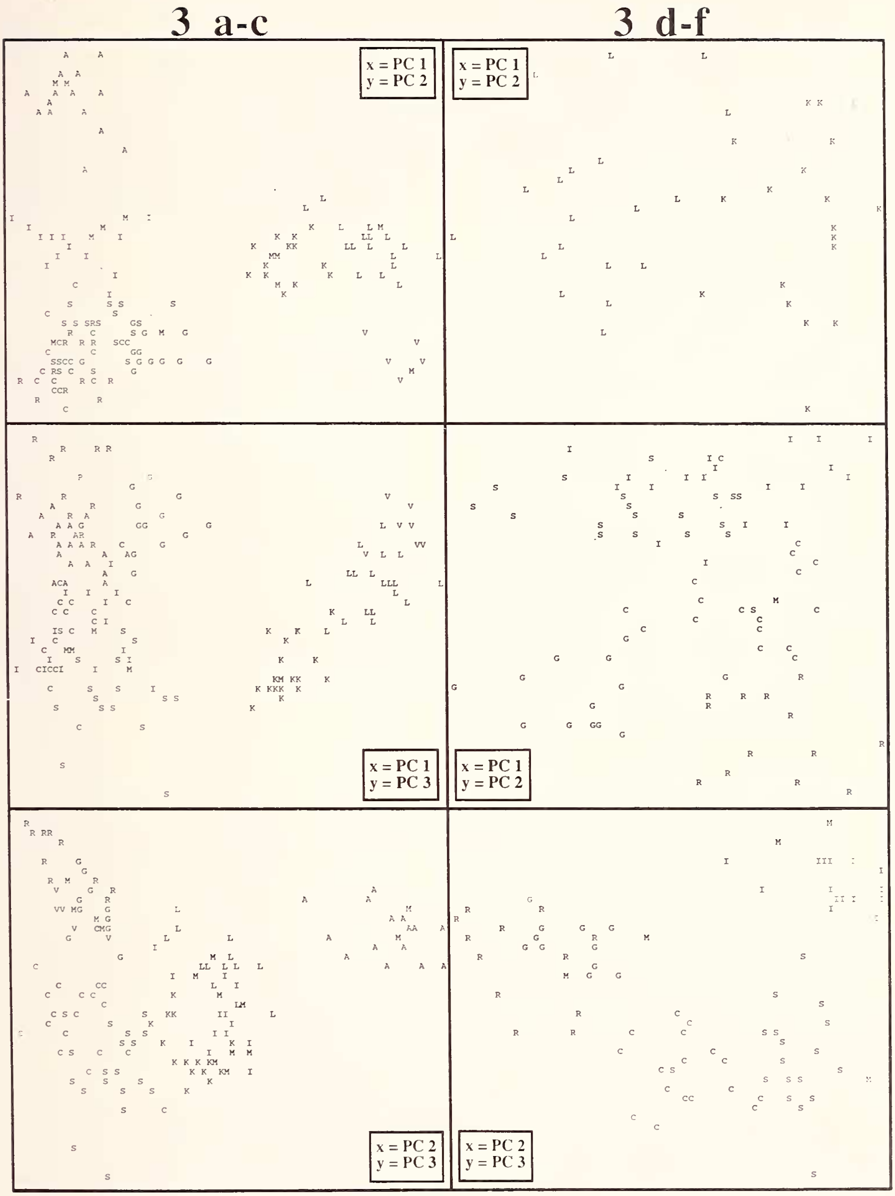

Fig. 3: Plots 1—3. 3a—c shows plot 1, 3d shows plot 2 (first projection only), 3e—f shows plot 3, first (3e) and third (3f) projections. A = *S. alpinus*, C = *S. coronatus*, G = *S. granarius*, I = *S. isodon*, K = *S. caecutiens*, L = *S. minutus*, M = more than one individual (or for the variable plots, more than one variable) in the same spot, R = *S. samniticus*, S = *S. araneus*, V = *S. minutissimus*.

plot of the same material showed that the most important factors separating *S. alpinus* from all other species were a longer A^5, lacrimal foramen placed further back, a twocusped A_1 and mental foramen placed more anteriorly.

The separation of the remaining species into two groups were purely metric, the "*caecutiens-minutissimus-minutus*-group" included smaller animals than the other group. The separation of *S. minutissimus* from *S. caecutiens-minutus* was chiefly due to even smaller overall measurements and to the mental foramen positioned further back.

B. *Sorex caecutiens* and *S. minutus*

The second PCA plot (Fig. 3d) showed the two remaining species of the smaller group, *S. caecutiens* and *S. minutus*. At least the two first projections showed a gradual separation of the two species.

The first component explained 38.1 % of the variance, the other two did not contribute much, 4.8 % and 4.1 % of the total variance respectively, the total variance explained was 47 %. A discriminant PLS analysis applicated on these two species showed a clearly significant class separation according to cross validation (37.9 % of the variance explained by the first latent variable and 3.5 % by the second, a total of 41.5 %). The characters most important in separating the species were that *S. minutus* had larger medial tines, lacrimal foramen placed further back, mental foramen positioned more in front and smaller overall measurements than in *S. caecutiens*.

C. The remaining species

The third PCA plot (Fig. 3e—f) contained the five remaining forms, *S. araneus*, *S. coronatus*, *S. granarius*, *S. isodon* and *S. samniticus*. Four of them are very similar morphologically, while *S. isodon* is clearly distinguishable. It was somewhat surprising to find this species grouped together with the other four. The first component (Fig. 3e) explained 18.1 % of the variance and was clearly grouping the animals in size. The second component explained 14.8 % of the total variance, and here *S. isodon* tended to drift apart. The third component (Fig. 3f) finally set *S. isodon* very clearly apart from the other species, explaining 7.9 % of the total variance, the total variance explained was 40.7 %. Discriminant PLS analyses between *S. isodon* and each of the four remaining forms did, however, not show any greater significance than discriminant PLS between these other species, the variance explained was 30.8 % for *S. isodon* — *S. araneus*, 29.8 % for *S. isodon* — *S. coronatus*, 40.1 % for *S. isodon* — *S. granarius* and 30.8 % for *S. isodon* — *S. samniticus* while the variance explained by PLS between the other four species was between 22.8 % and 37.2 % (see below).

Variables separating *S. isodon* from the other four species (see variable plot, Fig. 4a) were: 1. Longer antemolar toothrow in upper jaw; 2. Distinctly larger A^5; 3. Lesser width of P^4 and M^1; 4. Lacrimal foramen placed further back; 5. Unpigmented hypocones on upper molars (separates only against *S. araneus* and *S. coronatus*); 6. Mental foramen placed in more frontal position.

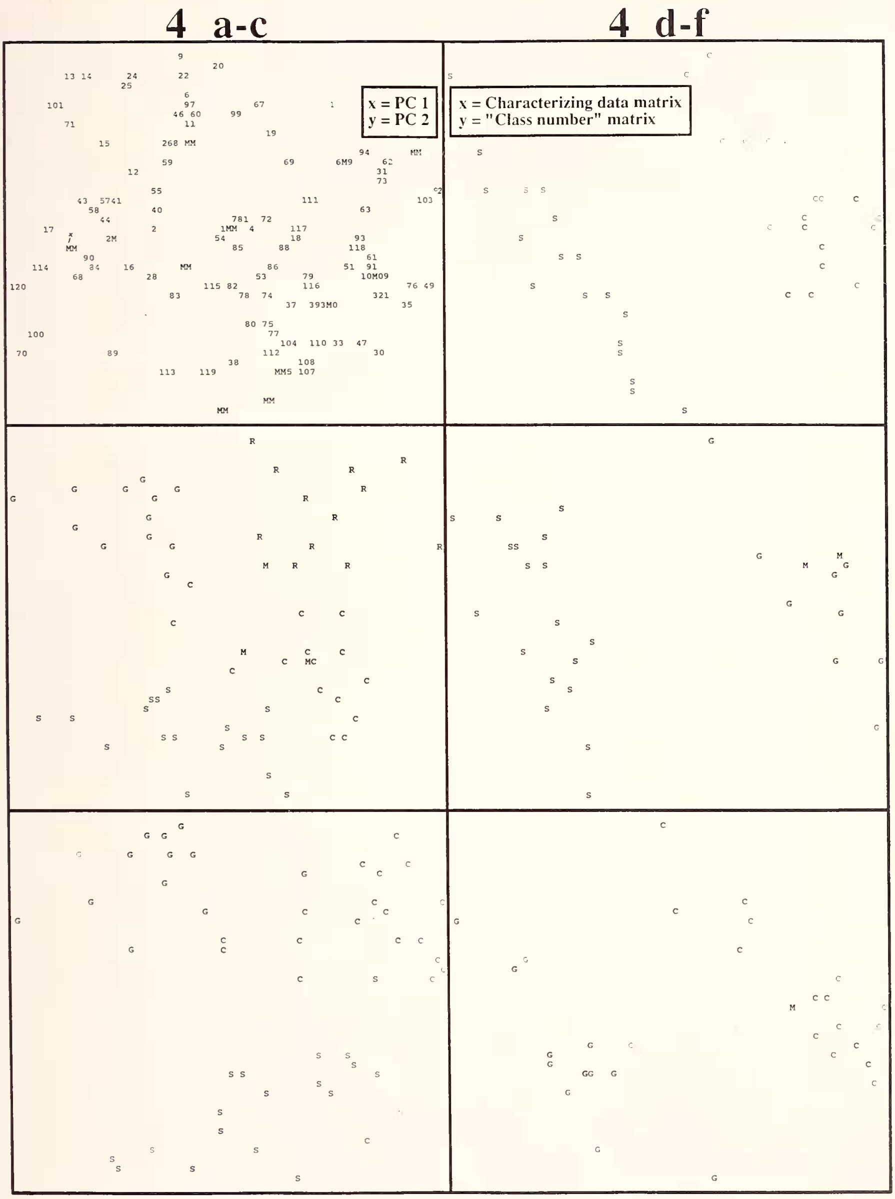

Fig. 4: 4a) A variable plot corresponding to Fig. 3e. 4b) plot 4 (first projection). 4c) plot 5 (first projection). 4d—f) PLS-plots for *S. araneus* — *S. coronatus* (4d), *S. araneus* — *S. granarius* (4e) and *S. coronatus* — *S. granarius* (4f).

Table 2: Mean values and standard deviation (s) of measurements taken in mm (see Material and methods). Only the continuous metrical measurements are included in this table, and for those taken both on left and right side, only those taken on the left are given. Readers interested in the remaining values can obtain these from the author. A = *S. alpinus*, B = *S. araneus*, C = *S. caecutiens*, D = *S. coronatus*, E = *S. granarius*, F = *S. isodon*, G = *S. minutissimus*, H = *S. minutus*, I = *S. samniticus*.

	A	B	C	D	E	F	G	H	I
1	17.704	17.046	15.274	17.263	15.836	17.768	11.852	14.060	16.581
s	0.451	0.635	0.554	0.480	0.493	0.603	0.526	0.726	0.476
2	1.138	1.387	1.116	1.496	1.316	1.254	0.900	0.963	1.270
s	0.140	0.140	0.146	0.122	0.151	0.189	0.076	0.090	0.101
3	4.833	4.539	3.800	4.903	4.621	4.782	3.629	3.490	4.926
s	0.159	0.360	0.189	0.189	0.185	0.308	0.154	0.179	0.146
4	3.943	3.397	2.964	3.466	3.516	3.665	2.550	2.660	3.513
s	0.130	0.238	0.142	0.150	0.121	0.228	0.079	0.109	0.066
6	5.583	5.553	5.077	5.441	5.185	6.130	3.409	4.400	4.999
s	0.243	0.304	0.314	0.240	0.162	0.604	0.280	0.348	0.241
7	1.513	1.812	1.542	1.803	1.580	1.630	1.299	1.175	1.746
s	0.073	0.125	0.079	0.139	0.130	0.158	0.082	0.075	0.133
8	1.095	1.352	1.130	1.293	1.175	1.253	0.961	0.883	1.169
s	0.071	0.139	0.063	0.144	0.094	0.110	0.075	0.072	0.069
9	2.805	2.444	2.127	2.336	2.013	2.561	1.325	1.834	2.111
s	0.113	0.115	0.122	0.149	0.068	0.151	0.085	0.129	0.096
10	4.369	4.075	3.400	4.087	3.980	4.086	3.041	3.149	4.400
s	0.119	0.270	0.187	0.137	0.166	0.146	0.088	0.225	0.177
11	0.821	0.810	0.720	0.805	0.678	0.778	0.516	0.557	0.689
s	0.054	0.062	0.085	0.044	0.067	0.094	0.065	0.053	0.079
12	0.730	0.794	0.608	0.771	0.632	0.656	0.418	0.502	0.673
s	0.048	0.065	0.067	0.054	0.051	0.093	0.020	0.044	0.067
13	0.665	0.646	0.536	0.577	0.499	0.596	0.384	0.504	0.477
s	0.043	0.064	0.051	0.051	0.049	0.061	0.044	0.050	0.036
14	0.572	0.524	0.444	0.447	0.401	0.500	0.306	0.408	0.367
s	0.048	0.052	0.050	0.044	0.042	0.067	0.028	0.048	0.061
15	0.465	0.300	0.264	0.242	0.250	0.365	0.184	0.262	0.305
s	0.054	0.051	0.034	0.044	0.028	0.050	0.024	0.043	0.038
16	1.209	1.402	1.195	1.464	1.496	1.369	1.035	0.924	1.327
s	0.089	0.159	0.113	0.151	0.100	0.217	0.116	0.134	0.126
29	9.032	8.498	7.791	8.853	8.435	9.307	5.978	6.935	8.625
s	0.197	0.464	0.454	0.240	0.253	0.427	0.113	0.283	0.136
30	4.686	4.456	3.659	4.760	4.602	4.618	3.529	3.374	4.963
s	0.149	0.335	0.108	0.147	0.126	0.230	0.076	0.162	0.161
31	7.780	7.183	6.393	7.582	6.972	7.791	4.951	5.755	7.404
s	0.221	0.271	0.242	0.288	0.268	0.306	0.170	0.249	0.164
32	5.074	4.833	4.096	4.967	4.817	4.899	3.624	3.794	5.189
s	0.257	0.255	0.176	0.247	0.164	0.240	0.337	0.173	0.141
33	1.465	1.335	1.108	1.446	1.362	1.339	1.012	1.080	1.472
s	0.065	0.074	0.040	0.084	0.063	0.074	0.022	0.094	0.067
34	1.343	1.258	1.010	1.364	1.341	1.160	1.029	1.004	1.478
s	0.054	0.093	0.053	0.084	0.048	0.075	0.047	0.057	0.080

	A	B	C	D	E	F	G	H	I
35	1.259	1.220	1.081	1.312	1.194	1.272	1.003	0.972	1.355
s	0.051	0.081	0.038	0.069	0.075	0.076	0.046	0.068	0.044
36	1.319	1.279	1.020	1.376	1.326	1.160	1.056	0.990	1.480
s	0.063	0.071	0.057	0.081	0.044	0.057	0.068	0.057	0.064
37	1.154	1.025	0.936	1.050	1.056	1.105	0.876	0.853	1.161
s	0.036	0.083	0.053	0.067	0.082	0.063	0.069	0.053	0.048
38	1.253	1.269	1.003	1.276	1.233	1.144	1.060	0.974	1.391
s	0.057	0.110	0.053	0.057	0.074	0.081	0.068	0.052	0.094
39	0.753	0.641	0.624	0.755	0.714	0.759	0.539	0.576	0.782
s	0.038	0.058	0.033	0.052	0.042	0.056	0.021	0.038	0.063
40	1.155	1.278	0.978	1.141	1.100	1.158	0.963	0.935	1.185
s	0.046	0.127	0.045	0.081	0.056	0.091	0.060	0.058	0.084
61	8.998	7.715	6.672	8.166	7.945	8.414	5.394	6.078	8.305
s	0.412	0.312	0.262	0.241	0.297	0.338	0.144	0.224	0.311
62	3.706	4.038	3.186	4.211	3.758	4.273	2.748	2.691	4.105
s	0.132	0.145	0.119	0.125	0.184	0.184	0.071	0.187	0.107
63	2.520	2.700	2.290	3.023	2.616	2.935	2.066	2.042	2.822
s	0.145	0.191	0.123	0.168	0.205	0.167	0.031	0.117	0.101
64	3.196	3.448	3.145	3.584	3.118	3.431	2.307	2.501	3.380
s	0.136	0.193	0.123	0.135	0.183	0.169	0.089	0.171	0.072
66	5.166	4.705	4.005	4.736	4.377	4.995	3.323	3.680	4.766
s	0.207	0.220	0.131	0.128	0.114	0.204	0.129	0.213	0.179
67	1.077	0.947	0.794	0.902	0.810	1.012	0.550	0.706	0.861
s	0.038	0.079	0.072	0.066	0.067	0.093	0.029	0.092	0.088
69	0.997	1.059	0.917	1.049	0.987	1.120	0.779	0.828	1.056
s	0.091	0.075	0.046	0.069	0.093	0.083	0.042	0.060	0.084
71	1.344	1.831	1.244	1.473	1.226	1.555	0.980	1.061	1.380
s	0.146	0.152	0.185	0.199	0.141	0.178	0.066	0.167	0.170
72	0.997	0.984	0.751	1.066	0.935	0.994	0.540	0.711	1.006
s	0.091	0.103	0.066	0.070	0.063	0.065	0.061	0.080	0.083
73	1.386	1.339	1.162	1.359	1.284	1.397	0.991	1.047	1.355
s	0.052	0.071	0.041	0.059	0.054	0.059	0.047	0.050	0.069
74	0.820	0.832	0.623	0.842	0.824	0.863	0.635	0.568	0.916
s	0.044	0.057	0.041	0.054	0.069	0.066	0.034	0.039	0.057
75	0.904	0.885	0.647	0.894	0.869	0.880	0.630	0.630	0.971
s	0.054	0.058	0.040	0.049	0.061	0.054	0.033	0.039	0.051
76	1.156	1.086	0.954	1.151	1.058	1.132	0.898	0.904	1.171
s	0.040	0.061	0.025	0.050	0.048	0.040	0.039	0.044	0.046
77	0.814	0.798	0.593	0.815	0.810	0.821	0.635	0.574	0.916
s	0.047	0.059	0.046	0.051	0.065	0.067	0.037	0.034	0.062
78	0.863	0.819	0.609	0.811	0.820	0.844	0.631	0.603	0.898
s	0.048	0.052	0.052	0.053	0.062	0.064	0.054	0.040	0.056
79	0.968	0.928	0.840	0.940	0.881	0.938	0.775	0.793	0.987
s	0.046	0.061	0.038	0.040	0.047	0.049	0.060	0.044	0.054
80	0.705	0.653	0.504	0.662	0.681	0.681	0.507	0.497	0.754
s	0.029	0.038	0.040	0.048	0.062	0.045	0.023	0.042	0.059
81	0.597	0.586	0.428	0.526	0.526	0.580	0.377	0.421	0.580
s	0.035	0.061	0.040	0.063	0.050	0.053	0.042	0.037	0.049

	A	B	C	D	E	F	G	H	I
82	0.785	0.787	0.613	0.813	0.799	0.790	0.533	0.539	0.810
s	0.065	0.097	0.055	0.072	0.061	0.064	0.063	0.072	0.070
83	0.303	0.315	0.266	0.350	0.320	0.303	0.225	0.238	0.338
s	0.036	0.040	0.030	0.054	0.023	0.042	0.043	0.048	0.027
85	1.880	1.554	1.405	1.715	1.579	1.585	1.092	1.210	1.559
s	0.112	0.127	0.102	0.137	0.132	0.149	0.056	0.108	0.101
86	2.026	1.763	1.526	1.989	1.810	1.824	1.284	1.335	1.815
s	0.115	0.130	0.066	0.147	0.097	0.141	0.064	0.098	0.090
87	0.562	0.678	0.508	0.659	0.650	0.702	0.515	0.457	0.686
s	0.042	0.064	0.048	0.053	0.060	0.087	0.040	0.038	0.058
88	1.125	1.130	0.906	1.154	1.061	1.122	0.885	0.771	1.157
s	0.054	0.092	0.058	0.065	0.063	0.093	0.060	0.064	0.060
89	0.417	0.389	0.315	0.423	0.426	0.360	0.304	0.287	0.417
s	0.043	0.037	0.035	0.043	0.038	0.046	0.043	0.035	0.036

D. *S. araneus*, *S. coronatus*, *S. granarius* and *S. samniticus*

After the first three PCAs all species are separated except the four morphologically very similar species treated by Hausser (1984). A PCA was made on all four species (Fig. 4b), another one on the three members of the *S. araneus/arcticus*-group (Fig. 4c), and finally discriminant PLS analyses were made between all the species, two and two at a time (Fig. 4d–f). The PCA on all four species showed rather good separation of all four species in the first component (Fig. 4b) (which explained 20.9 % of the variance), clear separation of *S. coronatus* in the second component (explaining 16.5 %) and separation of *S. araneus* and *S. coronatus* but not of the other two species in the third (explaining 5.9 %); the total variance explained was 43.3 %.

The PCA on *S. araneus*, *S. coronatus* and *S. granarius* showed good separation of all three species in the first (Fig. 4c) and third components, less so in the second. The components explained respectively 22.1 %, 13.3 % and 5.0 % of the variance, a total of 40.4 %. In this PCA some strong outliers occurred, one very strong outlier of *S. araneus* in the second and third projections was due to a measuring fault, but another *S. araneus* was separated among the *S. coronatus* in the third projection. This individual had a greater width and length of M^1 than other skulls of the same species (the differences were, however, very slight). Finally one *S. coronatus* was separated very clearly among the *S. araneus* in the first and third projections, due to a longer total length of the upper antemolars and larger height of the internal temporal fossa. In this last case the possibility of misidentification of the skull cannot be excluded.

Discriminant PLS analyses applicated on the different species, two and two at a time, showed good separation of all the species. The variance explained was 27.3 % for *S. araneus* — *S. coronatus* (Fig. 4d), 34.5 % for *S. araneus* — *S. granarius* (Fig.

4e), 35.7 % for *S. coronatus* — *S. granarius* (Fig. 4f), 37.2 % for *S. araneus* — *S. samniticus*, 22.8 % for *S. coronatus* — *S. samniticus* and 35.7 % for *S. granarius* — *S. samniticus*.

A discriminant PLS applicated on all four species simultaneously showed, however, nothing not already present in the PCAs, it explained a total of 43 % of the variance.

The characters separating the four species were mostly metric and in almost all cases the measurements were overlapping, which made identification in this group very difficult. *S. samniticus* has, however, a few distinct characters such as the shape of the upper incisor (Graf et al. 1979; this character was not included in the present measuring program) and the position of medial tines on the same tooth (Dannelid 1989). Also one difference that seemed fairly constant was that *S. samniticus* showed greater width over the trigonids on the lower molars than the other species. Apart from that all of these species were very similar. Statements on size differences refer to the mean values.

Characters separating *S. araneus* from:

a) *S. coronatus*: Condylobasal length shorter, upper antemolar toothrow longer, width and length of M^1 smaller. Mandible shorter and width and length of M_3 smaller, height of internal temporal fossa larger.

b) *S. granarius*: Overall larger measurements, especially the condylobasal length and the upper antemolar toothrow, lacrimal foramen placed a little more anteriorly.

c) *S. samniticus*: Condylobasal length larger, palatal length shorter, glenoid width shorter, width of molars (especially trigonid width of lower molars) smaller.

Characters separating *S. coronatus* from:

a) *S. granarius*: The same as those separating *S. araneus* from *S. granarius*.

b) *S. samniticus*: Condylobasal length larger, trigonid width of lower molars smaller.

Characters separating *S. granarius* from *S. samniticus*: Coronoid process lower, trigonid width of lower molars much smaller (overlapping very little).

Also by using several metric characters like condylobasal length, length of upper antemolar toothrow and length of first upper antemolar it was possible to build two groups, one consisting of larger forms (*S. araneus* and *S. coronatus*) and one consisting of smaller forms (*S. granarius* and *S. samniticus*). However, *S. coronatus* and *S. samniticus* had a greater palatal length than *S. araneus* and *S. granarius*. *S. samniticus* showed greater width between the M^2 than the other species. *S. araneus* clearly showed a greather height of the internal temporal fossa than the remaining species. *S. granarius* showed lesser height of the coronoid process than the other three species.

The characters mentioned are not all separating the different species but are those which, from the variable plots, appear to be most important. It must be remembered that since almost all measurements overlap it is a combination of characters, not the characters themselves, that separates the species. Hausser & Jammot (1974) found four characters by which it was possible to make a 95,3 % discrimination between *S. araneus* and *S. coronatus*, none of these characters was, however, included in the present study.

Discussion

The plots made a clear distinction between most of the *Sorex*-species analysed in this work. This is not, however, necessarily a phylogenetic distinction. It must be remembered that statistical methods applied on pure skull morphology may sometimes more reflect the overall similarity rather than the phylogeny, since it is hard to detect convergences and parallel evolutions with these methods. For example *S. caecutiens*, *S. minutissimus* and *S. minutus* were discriminated against the other species chiefly because of their smaller size. Increase and decrease in size, however, might have occurred many times in different *Sorex*-lineages.

If the plots should give good information they have to be compared with karyological and electrophoretical data. *S. alpinus* was the most isolated species according to the plots, and this is also the case according to electrophoresis (Catzeflis et al. 1982) and probably also to the karyotype (Meylan 1964). Apparently this species has got no close relatives in Europe (and probably nowhere else), it must be regarded as an old relic species.

In the case of *S. alpinus* all data point in one direction; this is, however, not the case with the second group separated in the plots, the smaller species *S. caecutiens*, *S. minutissimus* and *S. minutus*. They are separated chiefly because they are smaller; but within the group considerable size differences are present. Karyologically all belong to a "group" characterized by a chromosomal number of 42 or close to 42, but this group might not be a natural one. Electrophoretical results indicate that the three small species do not form a phylogenetic group (Catzeflis 1984, in his work *S. minutissimus* was not included). They are probably species with plesiomorphous chromosome characters (they lack the sex chromosome specialisations of the *S. araneus/arcticus*-group), but this also applies to *S. isodon* and *S. samniticus*.

Of the five remaining species, *S. isodon* was clearly separated from the others in the plots. Karyologically, *S. isodon* is most similar to *S. caecutiens*. It might well be argued that *S. isodon* and *S. caecutiens* are related and that the plot discriminance between them is due chiefly to size differences.

The four remaining species make up the troublesome part. They are all very similar morphologically and it is only possible to separate them chiefly by using a combination of characters. However, chromosomes and electrophoresis give another view: *S. araneus*, *S. coronatus* and *S. granarius* are closely related while *S. samniticus* remains very much apart. Hausser (1984) made statistical analyses of these four species using SPSS, using not only principal component and discriminant analyses as in this work, but also multiple regression and canonical correlation analyses. He also included geoclimatic variables which is outside the scope of this work. He stated convincingly that the morphological differences between the four species could be partly explained by habitat conditions but not by ecological shifts into new niches. His conclusion was that the "*araneus*"-niche was a highly successful one that allowed animals to exist for a long time morphologically unchanged. *S. samniticus* might thus be a remnant of earlier *Sorex*-occupants of this niche, or it might (less likely) be the result of an isolated Italian speciation into that niche.

A comparison between the karyological data, the electrophoretical data and the morphological data (as expressed in these plots) indicates that the phylogeny is more consistently reflected in the karyological and electrophoretical data, while the morphological data reflects both phylogenetic and ecological differences. In some cases (the position of *S. alpinus* and the close relationship of *S. araneus* — *S. coronatus* — *S. granarius*) the morphological results are in accordance with results achieved by cytological research and electrophoresis, in other cases not. In these cases the author suggests that similarities and differences in gross morphology should be regarded as the result of ecological adaptations.

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Zusammenfassung

Schädel von 9 Arten von Spitzmäusen der Gattung *Sorex* wurden mit Hilfe eines Bild-Analysators gemessen. Von jedem Schädel wurden 120 Messungen genommen. Diese wurden dann statistisch verarbeitet unter Verwendung multivariabler Analysenprogramme (SIMCA-package). Die Resultate zeigten deutliche Unterschiede zwischen allen Arten. Die morphologischen Ergebnisse werden mit Chromosomendaten und Elektrophoresebefunden verglichen und es wird diskutiert, inwieweit Unterschiede die Phylogenie widerspiegeln oder als Resultat ökologischer Anpassungsprozesse verstanden werden müssen.

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